

Performance characteristics of a quantum Diesel refrigeration cycle

Jizhou He^{*}, Hao Wang, Sanqiu Liu

Department of Physics, Nanchang University, Nanchang 330031, People's Republic of China

ARTICLE INFO

Article history:

Received 24 September 2007

Received in revised form 23 May 2008

Accepted 21 December 2008

Available online 7 February 2009

Keywords:

Diesel refrigeration cycle

Ideal quantum gas

Quantum degeneracy

Performance analysis

ABSTRACT

The Diesel refrigeration cycle using an ideal quantum gas as the working substance is called quantum Diesel refrigeration cycle, which is different from Carnot, Ericsson, Brayton, Otto and Stirling refrigeration cycles. For ideal quantum gases, a corrected equation of state, which considers the quantum behavior of gas particles, is used instead of the classical one. The purpose of this paper is to investigate the effect of quantum gas as the working substance on the performance of a quantum Diesel refrigeration cycle. It is found that coefficients of performance of the cycle are not affected by the quantum degeneracy of the working substance, which is the same as that of the classical Diesel refrigeration cycle. However, the refrigeration load is different from those of the classical Diesel refrigeration cycle. Lastly, the influence of the quantum degeneracy on the performance characteristics of the quantum Diesel refrigeration cycle operated in different temperature regions is discussed.

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1. Introduction

Quantum theory, a field opened by Planck and other pioneers in 20th century has intrigued scientists. Quantum thermodynamic cycles, such as quantum engine [1–4], quantum refrigerator [5], quantum heat pump [6], quantum amplifier [7], quantum afterburner [8], and so on [9–12], have become one of the interesting research subjects for people working in thermodynamics and statistical physics. These quantum analyses provide the application foundation of the equilibrium or non-equilibrium statistical mechanics to the practical engineering cycles. Several authors have intensively investigated the performance characteristics of quantum thermodynamic cycles working with particles in a potential [1], uncoupled spins [2], harmonic oscillators [3], two level systems [5], multi-level systems [4] or quantum optics systems [8–10], etc.

The Diesel cycle is one of the important cycle models in the research and manufacture. Based on the equation of state of an ideal classical gas, many novel results of the Diesel cycle are obtained [13–19]. Recently, the thermodynamic performance parameters of the Carnot [20], Stirling [21–23], Ericsson [24], Brayton [25,26] and Otto [27–29] cycles working with an ideal quantum gas have been investigated by a number of researchers. The performance characteristics of these cycles are analyzed under the condition of the quantum degeneracy. However, most of the previous works have concentrated on the performance analysis of the above these

cycles. The performance analysis of the Diesel refrigeration cycle working with an ideal quantum gases has been rarely considered.

In this paper, the quantum models of Diesel refrigeration cycle working with ideal Fermi (^3He) and Bose (^4He) type quantum gas are established, which are called Bose or Fermi Diesel refrigeration cycle, respectively. Based on the corrected equation of state of an ideal quantum gas, the general expressions of the coefficient of performance and refrigeration load of the cycle are derived. The influence of the quantum degeneracy on the performance parameters of the cycle is discussed. The results of the work obtained here will be compared with other quantum gas refrigeration cycles.

2. A gas Diesel refrigeration cycle

A Diesel refrigeration-cycle using an ideal quantum gas as the working substance is composed of one isobaric, one isochoric and two isentropic processes. According to the expression of the entropy of an ideal gas, one can easily give the T – S diagram of a Diesel refrigeration cycle, as shown in Fig. 1. Process 1–2 is an isentropic compression. Processes 2–3 and 4–1 are isobaric heat rejection and isochoric heat addition, respectively. Process 3–4 is an isentropic expansion. Q_H and Q_L are the amounts of heat exchange between the working substance and the heat reservoirs at temperatures T_H and T_L during isobaric 2–3 and isochoric 4–1 processes; where p_H is the highest pressure of the working substance in the cycle, v_H is the maximum average volume that a particle occupies. T_H and T_L are the temperatures of the hot reservoir and cold reservoir. The temperatures of state points 1, 2, 3, and 4 are represented by T_1 , T_2 , T_3 and T_4 , respectively.

^{*} Corresponding author. Tel./fax: +86 791 8305626.

E-mail address: hjzhou@ncu.edu.cn (J. He).

Nomenclature

C_p	heat capacity at constant pressure (J/K)
C_v	heat capacity at constant volume (J/K)
$F(z)$	correction function
g	weight factor
h	Planck's constant (Js)
k	Boltzmann constant (J/K)
m	rest mass of a particle (kg)
N	total number of particles
N_0	particle number in the ground state
n	number density (m^{-3})
P	pressure (Pa)
P_H	maximum pressure (Pa)
Q_H	amount of heat exchange between the working substance and the heat reservoir during the high constant-pressure process (J)
Q_L	amount of heat exchange between the working substance and the heat reservoir during the high constant-volume process (J)
R_{QL}	relative refrigeration load

S	entropy (J/K)
T	absolute temperature (K)
T_H	temperature of heat reservoir (K)
T_L	temperature of cold reservoir (K)
U	internal energy (J)
V	volume (m^3)
W	work input (J)
z	fugacity of the gas

Greek symbols

ε	coefficient of performance
λ	mean thermal wavelength (m)
μ	chemical potential of the gas (J)
τ	temperature ratio of two heat reservoirs
k	Boltzmann's constant
$\Gamma(l)$	Gamma function
$\zeta(l)$	Riemann-Zeta function

3. Thermodynamic properties of an ideal quantum gas

Based on quantum statistics, the expressions for the pressure and number density of an ideal Fermi gases are given as follows [30]

$$P = \frac{gkTf_{5/2}(z)}{\lambda^3} \quad (1)$$

$$n = \frac{N}{V} = \frac{1}{v} = \frac{gf_{3/2}(z)}{\lambda^3} \quad (2)$$

where $f_l(z) = \frac{1}{\Gamma(l)} \int_0^\infty \frac{x^{l-1}}{z^{-1}e^x + 1} dx$ is called the Fermi function and g is a weight factor that arises from the “internal structure” of the particles (such as spin), k is the Boltzmann's constant, T is the gas temperature, N is the total number of the particles, and V is the volume of the gas, v is the occupied volume of the particle, $\lambda = h(2\pi mkT)^{-1/2}$ is the mean thermal wavelength of the particles, h is Planck's constant, m is the rest mass of the particles, $f_l(z)$ is called the Fermi function, $z = \exp[\mu/kT]$ is the fugacity of the gas, $\Gamma(l)$ is the Gamma function and μ is the chemical potential of the gas.

For an ideal Bose gas the expressions for the pressure and the number density are given as follows [30]

$$P = \frac{kTg_{5/2}(z)}{\lambda^3} \quad (3)$$

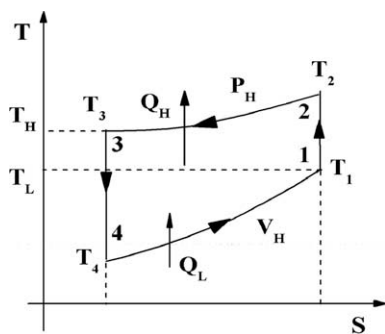


Fig. 1. Temperature-entropy diagram of a Diesel refrigeration cycle.

$$n = \frac{N - N_0}{V} = \frac{1}{v} = \frac{g_{3/2}(z)}{\lambda^3} \quad (4)$$

where N_0 is the number of the particles in ground state, while $g_l(z) = \frac{1}{\Gamma(l)} \int_0^\infty \frac{x^{l-1}}{z^{-1}e^x - 1} dx$ is called the Bose function.

The equation of state for an ideal quantum gas may be written as [24]

$$P = nkTF(z) \quad (5)$$

where $F(z)$ is called the correction factor which is defined for a Fermi gas as

$$F(z) = \frac{f_{5/2}(z)}{f_{3/2}(z)} \quad (6)$$

The correction factor for a Bose gas is

$$F(z) = \frac{g_{5/2}(z)}{g_{3/2}(z)} \left(\frac{T}{T_c} \right)^{3/2} \left\{ \left[\left(\frac{T_c}{T} \right)^{3/2} - 1 \right] \theta(T - T_c) + 1 \right\} \quad (7)$$

$$\theta(T - T_c) = \begin{cases} 1 & (T > T_c) \\ 0 & (T < T_c) \end{cases}$$

where T_c is the Bose-Einstein condensation temperature defined as

$$T_c = \frac{h^2}{2\pi mk} \left[\frac{N}{V\zeta(3/2)} \right]^{2/3} = \frac{h^2}{2\pi mk} (v\zeta(3/2))^{-2/3} \quad (8)$$

where $\zeta(3/2) = 2.612$.

The internal energy and the specific heat at constant volume of an ideal quantum gas are given by

$$U = \frac{3}{2} NkTF(z) \quad (9)$$

$$C_v = \left(\frac{\partial U}{\partial T} \right)_v = \frac{3}{2} Nk \frac{d}{dT} [TF(T, v)] \quad (10)$$

$$C_p = C_v + T \left(\frac{\partial P}{\partial T} \right)_v \left(\frac{\partial V}{\partial T} \right)_p \quad (11)$$

Substituting Eqs. (5) and (10) into Eqs. (11), one can obtain

$$C_p = \frac{5}{2} Nk \frac{d}{dT} [TF(T, p)] \quad (12)$$

where the correction factor $F(T, v)$ is a function of temperature T and volume v , the correction factor, $F(T, p)$ is a function of temperature T and pressures p . Using Eqs. (11) and (12), one can calculate the amounts of heat exchange in isochoric and isobaric processes. They are given by

$$Q_{if}^v = \int_i^f C_v(T, v) dT = \frac{3}{2} Nk [T_f F(T_f, v) - T_i F(T_i, v)] \quad (13)$$

and

$$Q_{if}^p = \int_i^f C_p(T, p) dT = \frac{5}{2} Nk [T_f F(T_f, p) - T_i F(T_i, p)] \quad (14)$$

where the indices i and f refer to the initial and final states, respectively. We can analyze the Diesel refrigeration cycle working with an ideal quantum gas with the help of Eqs. (13) and (14).

4. The effect of quantum degeneracy

Since the entropy s of the system and the correction factors $F(z)$ only depend on z , the expressions in the isentropic processes 1–2 and 3–4 can be obtained

$$F(T_L, v_H) = F(T_2, p_H) \quad (15)$$

$$F(T_H, p_H) = F(T_4, v_H) \quad (16)$$

Because of this property of the correction factors, quantum and classical ideal-gases have the same isentropic relations between temperature, pressure and specific volume. Consequently, for the isentropic processes 1–2 and 3–4, one can obtain the following equations:

$$\frac{v_H}{v_2} = \left(\frac{p_2}{p_1}\right)^{\frac{3}{5}} = \left(\frac{T_2}{T_L}\right)^{\frac{3}{2}} \quad (17)$$

$$\frac{v_H}{v_2 3} = \left(\frac{p_3}{p_4}\right)^{\frac{3}{5}} = \left(\frac{T_H}{T_4}\right)^{\frac{3}{2}} \quad (18)$$

Using Eq. (5), for the isobaric process 2–3 and the isochoric process 4–1, one can obtain

$$\frac{T_2}{T_H} = \frac{v_2}{v_3} \frac{F(T_H, p_H)}{F(T_2, p_H)} \quad (19)$$

$$\frac{T_4}{T_L} = \frac{p_4}{p_1} \frac{F(T_L, v_H)}{F(T_4, v_H)} \quad (20)$$

Using Eqs. (17) and (19), yields

$$\frac{T_L}{T_H} = \left(\frac{T_L}{T_2}\right) \left(\frac{T_2}{T_H}\right) = \left(\frac{v_2}{v_H}\right)^{\frac{2}{3}} \frac{v_2}{v_3} \frac{F(T_H, p_H)}{F(T_2, p_H)} \quad (21)$$

The amounts of heat exchange, Q_L during isochoric 4–1 process and Q_H during isobaric 2–3 process, are obtained

$$Q_L = \int_{T_4}^{T_1} C_v dT = \int_{T_4}^{T_L} C_v dT = \frac{3}{2} Nk [T_L F(T_L, v_H) - T_4 F(T_4, v_H)] \quad (22)$$

$$Q_H = \left| \int_{T_2}^{T_3} C_p dT \right| = \int_{T_H}^{T_2} C_p dT = \frac{5}{2} Nk [T_2 F(T_2, p_H) - T_H F(T_H, p_H)] \quad (23)$$

where $T_H = T_3$, $T_L = T_1$, $v_1 = v_4 = v_H$ and $p_2 = p_3 = p_H$ (see Fig. 1). Using Eqs. (16), (20), and (22), yields

$$Q_L = \int_{T_4}^{T_L} C_v dT = \frac{3}{2} Nk T_L F(T_L, v_H) \left[1 - \left(\frac{v_2}{v_3}\right)^{\frac{5}{3}} \right] \quad (24)$$

Using Eqs. (16), (18), (21), and (22), yields

$$Q_L = \int_{T_4}^{T_L} C_v dT = \frac{3}{2} Nk T_H F(T_H, p_H) \left[\left(\frac{v_2}{v_H}\right)^{\frac{2}{3}} \frac{v_2}{v_3} - \left(\frac{v_3}{v_H}\right)^{\frac{2}{3}} \right] \quad (25)$$

Using Eqs. (19) and (23), one can obtain

$$Q_H = \int_{T_H}^{T_2} C_p dT = \frac{5}{2} Nk T_H F(T_H, p_H) \left[\frac{v_2}{v_3} - 1 \right] \quad (26)$$

5. Expressions for several important parameters

The net work is easily obtained by Eqs. (25) and (26) as follows:

$$W = Q_H - Q_L = \frac{5}{2} Nk T_H F(T_H, p_H) \left\{ \left[1 - \frac{3}{5} \left(\frac{v_2}{v_H}\right)^{\frac{2}{3}} \right] \frac{v_2}{v_3} - \left[1 - \frac{3}{5} \left(\frac{v_3}{v_H}\right)^{\frac{2}{3}} \right] \right\} \quad (27)$$

Using Eqs. (26) and (27), the coefficient of performance (COP) is written as

$$\varepsilon = \frac{Q_L}{W} = \frac{1}{\frac{Q_H}{Q_L} - 1} = \frac{1}{\frac{5}{3} \frac{v_2^{\frac{2}{3}}}{v_H^{\frac{2}{3}}} \frac{v_2 - v_3}{v_3^{\frac{2}{3}} - v_3^{\frac{2}{3}}} - 1} \quad (28)$$

Eq. (28) is the same as that of the classical Diesel refrigeration cycle $\varepsilon^c = \frac{1}{\frac{5}{3} \frac{v_2^{\frac{2}{3}}}{v_H^{\frac{2}{3}}} \frac{v_2 - v_3}{v_3^{\frac{2}{3}} - v_3^{\frac{2}{3}}} - 1}$. It is understood that the COP value of the Diesel

refrigeration cycle is not affected by the quantum degeneracy of the refrigerant. In addition, in order to compare the performance of a quantum Diesel refrigeration cycle with that of a classical Diesel refrigeration cycle, we introduce the relative refrigeration load as follows

$$R_{QL} = \frac{Q_L}{Q_L^c} = F(T_H, p_H) \quad (29)$$

or

$$R_{QL} = \frac{Q_L}{Q_L^c} = F(T_L, v_H) \quad (30)$$

where $Q_L^c = \frac{3}{2} Nk T_H \left[\left(\frac{v_2}{v_H}\right)^{\frac{2}{3}} \frac{v_2}{v_3} - \left(\frac{v_3}{v_H}\right)^{\frac{2}{3}} \right]$ or $Q_L^c = \frac{3}{2} Nk T_L \left[1 - \left(\frac{v_2}{v_3}\right)^{\frac{5}{3}} \right]$ is the refrigeration load of a classical Diesel refrigeration cycle.

6. Several interesting cases

It is clearly seen from Eqs. (29) and (30) that, for a quantum Diesel refrigeration cycle, the relative refrigeration load is dependent on the temperature, volume, pressure and other parameters. It is obvious that there are different performance characteristics for the quantum Diesel refrigeration cycle operated in the different temperature regions. Some special cases are discussed.

6.1. Under the condition of strong gas degeneracy

In this case, the working gas is always completely a degenerate quantum gas throughout the cycle. The correction factor $F(z)$ of an ideal Fermi gas can be obtained in terms of v as [22,23]

$$F(T, v) = \frac{2T_F(v)}{5T} + \frac{\pi^2 T}{6T_F(v)} \quad (31)$$

where $T_F(v) = C v^{-\frac{2}{3}}$ is the Fermi temperature, $C = \frac{(3h^3/8\pi)^{\frac{2}{3}}}{2km}$ is a constant. By using Eq. (31), the relative refrigeration load Eq (30) can be rewritten as follows

$$R_{QL} = F(T_L, v_H) = \frac{2Cv_H^{-\frac{2}{3}}}{5T_L} + \frac{\pi^2 T_L}{6Cv_H^{\frac{2}{3}}} \quad (32)$$

Similarly, in this case, the correction factor $F(z)$ for an ideal Bose gas can be obtained in terms of v as

$$F(T, v) = \zeta\left(\frac{5}{2}\right) \left(\frac{2\pi mk}{h^2}\right)^{\frac{3}{2}} v T^{\frac{3}{2}} \quad (33)$$

Where $\zeta(\frac{5}{2}) = 1.341$. By using Eq. (33), the relative refrigeration loads Eq. (30) can be rewritten as follows

$$R_{QL} = F(T_L, v_H) = \zeta\left(\frac{5}{2}\right) \left(\frac{2\pi mk}{h^2}\right)^{\frac{3}{2}} v_H T_L^{\frac{3}{2}} \quad (34)$$

6.2. Under the condition of weak gas degeneracy

In this case, the working gas is in the high-temperature and low-density condition throughout the cycle. The correction factor $F(z)$ of an ideal Fermi gas can be obtained in terms of v as [22,23]

$$F(T, v) = 1 + \frac{G}{vT^{\frac{3}{2}}} \quad (35)$$

where $G = \frac{h^3}{32(\pi mk)^{\frac{3}{2}}}$ is a constant. By using Eq. (35), the relative refrigeration loads Eq. (30) can be rewritten as follows

$$R_{QL} = F(T_L, v_H) = 1 + \frac{G}{v_H T_L^{\frac{3}{2}}} \quad (36)$$

Similarly, in this case, the correction factor $F(z)$ for an ideal Bose gas can be obtained in terms of v as

$$F(T, v) = 1 - \frac{G}{vT^{\frac{3}{2}}} \quad (37)$$

where $G = \frac{h^3}{16(\pi mk)^{\frac{3}{2}}}$ is a constant. By using Eq. (37), the relative refrigeration load Eq. (30) can be rewritten as follows

$$R_{QL} = F(T_L, v_H) = 1 - \frac{G}{v_H T_L^{\frac{3}{2}}} \quad (38)$$

When the temperature of the gas is high enough and its density is low enough, the fugacity of an ideal quantum gas z is much smaller than unity. In such a case, $F(z) = 1$ and an ideal quantum gas becomes an ideal classical gas. The relative refrigeration load can be expressed as follows

$$R_{QL} = 1 \quad (39)$$

The results are just those of a classical Diesel refrigeration cycle. This shows clearly that, at high temperatures, the quantum Diesel refrigeration cycle becomes the classical cycle.

7. Discussion

In Fig. 2, it is shown how the relative refrigeration load R_{QL}^F depends on the temperature T_L and the maximum occupied volume v_H of the particle in the case of Fermi gas. It shows clearly that under the condition of strong gas degeneracy, the refrigeration load R_{QL}^F is higher than that of weak gas degeneracy. For high values of temperature T_L , the relative refrigeration load R_{QL}^F goes to unity. This is the expected behavior since correction factors goes to unity for high values of temperature T_L and the refrigerant becomes a classical ideal gas.

In Fig. 3, it is shown how the relative refrigeration load R_{QL}^B depends on the temperature T_L and the maximum occupied volume v_H of the particle in the case of Bose gas. It shows clearly

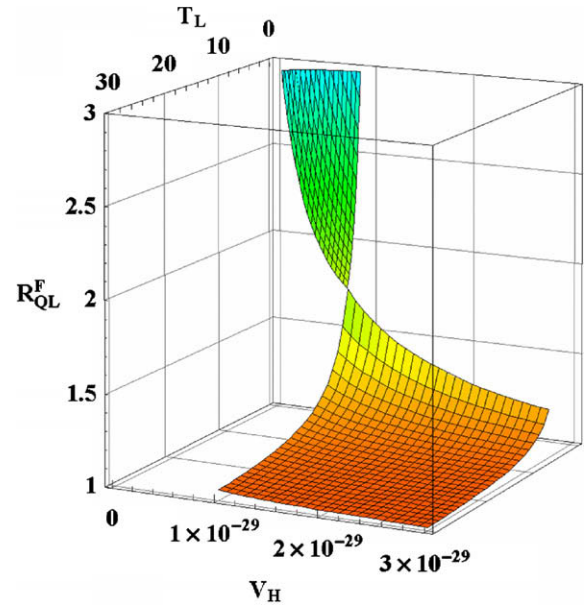


Fig. 2. The three-dimensional graph of the relative refrigeration load R_{QL}^F varying with the cold reservoir T_L and the maximum occupied volume v_H of the particle in the case of Fermi gas.

the refrigeration load R_{QL}^B under the condition of strong gas degeneracy is lower than that of weak gas degeneracy. For high values of temperature T_L , the relative refrigeration load R_{QL}^B goes to unity. This is also the expected behavior since correction factors goes to unity for high values of temperature T_L and the refrigerant becomes a classical ideal gas.

The relative refrigeration load R_{QL}^F and R_{QL}^B varying with the temperature T_L and the maximum occupied volume v_H of the particle are shown in Figs. 2 and 3. For low values of T_L and v_H , the relative refrigeration load R_{QL}^F and R_{QL}^B are different from the unity since quantum degeneracy becomes important. It is seen that R_{QL}^F is always greater than unity and R_{QL}^B is always lower than unity. On the other hand, the relative refrigeration load R_{QL}^F and R_{QL}^B go to

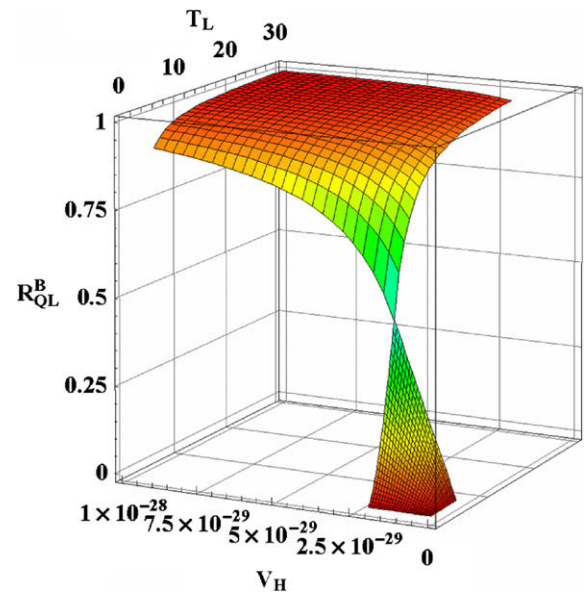


Fig. 3. The three-dimensional graph of the relative refrigeration load R_{QL}^B varying with the cold reservoir T_L and the maximum occupied volume v_H of the particle in the case of Bose gas.

unity for high values of T_L and v_H . It also can be seen that the relative refrigeration load of Diesel refrigeration cycle can be expressed as follows

$$R_{QL}^F > R_{QL}^C = 1 > R_{QL}^B \quad (40)$$

Moreover, unlike Bose–Brayton refrigeration cycle, the minimum value of the cold reservoir T_L for the Bose Diesel refrigeration cycle is not restricted by the Bose Einstein condensation temperature T_c .

8. Conclusion

In this paper, a thermodynamic model of the quantum Diesel refrigeration cycle has been established. The influence of the quantum degeneracy of the working fluid on the performance of a Diesel refrigeration cycle is analyzed. Under the quantum degeneracy conditions, it is shown that the refrigeration load of the Fermi Diesel cycle is always greater than that of the classical Diesel cycle. On the contrary, the refrigeration load of the Bose Diesel cycle is always lower than that of the classical one. Thus, in a Diesel refrigeration cycle using a Fermi-type refrigerant, more heat is absorbed per cycle from the cold reservoir by consuming more work per cycle. On the other hand, in a Diesel refrigeration cycle using a Bose-type refrigerant, less heat is absorbed per cycle from the cold reservoir by consuming less work per cycle. It can be said that the Fermi type of ideal gas is always advantageous for a Diesel refrigeration cycle since the same refrigeration load is obtained with a lower number of cycles. On the contrary, the Bose type of ideal gas is always disadvantageous because it causes an increment in the number of cycles for a given refrigeration load. Moreover, unlike Bose–Brayton refrigeration cycle, the minimum value of the cold reservoir T_L for the Bose Diesel refrigeration cycle is not restricted by the Bose Einstein condensation temperature T_c .

Acknowledgement

This work was supported by National Natural Science Foundation (No. 10765004), People's Republic of China.

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